Renewable and Sustainable Energy Reviews 16 (2012) 1971–1976

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy resources—The ultimate solution

Muhammad Shafiq Siraj *

Graz University of Technology, Graz, Austria

ARTICLE INFO

Article history:
Received 6 July 2011
Accepted 6 January 2012
Available online 18 February 2012

Keywords:
Energy
Renewable
Resource
SDES
SIES

ABSTRACT

Energy is vital for all types of activities on earth whether living or non-living. This paper first discusses some misconceptions about energy and energy sources. A new classification of energy sources, contrary to traditional renewable and non-renewable sources, is then presented. The energy sources are classified as sun-dependent energy sources (SDES) and sun-independent energy sources (SIES). Total energy use of the world, today and in the long future, and a possible energy scenario is proposed in the light of this new classification of energy sources. Unlike previous energy scenarios which cover few decades to a maximum of few centuries, this paper presents the energy use and policy guidelines for long into the future keeping in view the energy sources available at that time, their optimum utilization, total world population and energy-use-per-person constraints.

Contents

1. Introduction

1.1. Background

All types of activities, living or non-living, depend on energy. The energy is vital for all forms of life on earth. The ancient people realized its significance even before the invention of machines, thus making the major sources of energy e.g., the sun a deity in some cultures.

Energy, today, is even more important than before because all types of machine movements and working are dependent on the use of energy. A modern-life cannot be imagined without machines and machines cannot be imagined without the use of energy.

Some natural resources on earth like water – which though in a definite quantity and despite the fact of constant depletion of fresh water resources – is present on earth in a closed cycle i.e., water cycle. These resources (e.g., water) are going to be available almost forever unless an extraterrestrial catastrophe affecting the earth, for example, through collision of a large asteroid, happens..

Unfortunately, energy on earth is neither available in an indefinite quantity nor its utilization is in a closed cycle so that it is

* Tel.: +43 316 873 4887; Mobile: +43 69917159516.
E-mail addresses: m.s.siraj@tugraz.at, muhammad.shafiq.siraj@gmail.com

1364-0321/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2012.01.030

Nomenclature

SDES	sun-dependent energy sources
SIES	sun-independent energy sources
EJ	exa-joule
GJ	giga-joule

available almost forever. On the other hand, it is only available in definite quantities and will eventually be lost mostly to outer space in the form of infrared radiation – an inevitable fate [1]. The sun, which is normally considered an infinite source of energy, is, on the contrary, a typical example of a continuously depleting source. Consequently, all the resources on earth which are directly dependent on the sun hence are not renewable, in contrast to what is generally perceived as renewable resources. Therefore, a new classification of energy sources is given as the sun-dependent energy sources (SDES) and sun-independent energy sources (SIES).

1.2. Energy definition

A broader picture can be perceived more easily with a precise definition of energy. However, even some advanced texts do not define energy and simply go deeper into the discussion [2–7]. Some define energy as: the ability/capacity of a body or system to do work [8]. The author presents a modified new definition to energy as "the *ultimate* capacity of *anything* to do work".

1.3. Energy requirement estimates

Energy requirements depend on a number of factors: primarily, the prosperity of a nation; secondly, climatic conditions; and thirdly, efficient use of energy. The efficient use of energy depends on specific national policy of a country, mostly driven by the factor of self sufficiency of a country in energy resources.

Fig. 1 shows the historical world population figures since 1950 and projection till the year 2300 according to latest UN figures [9]. It shows three possible scenarios after year 2010: low, medium, and high. We will only consider the medium level increase scenario for our calculations involving world population. Previous UN studies [10] also suggested a similar trend for stabilization of world population at around 10 billion from around year 2200 onward.

As discussed, the primary energy consumption/requirement per person in the world depends on several factors e.g., prosperity of a nation, energy dependence on foreign resources, national policy,

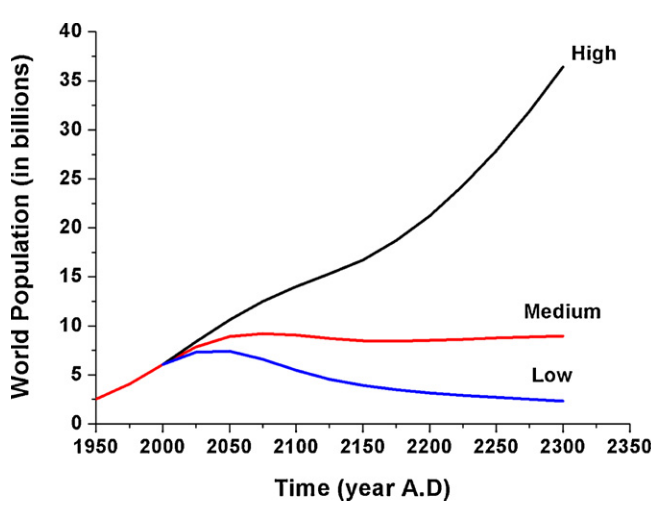


Fig. 1. World population – history and projection.

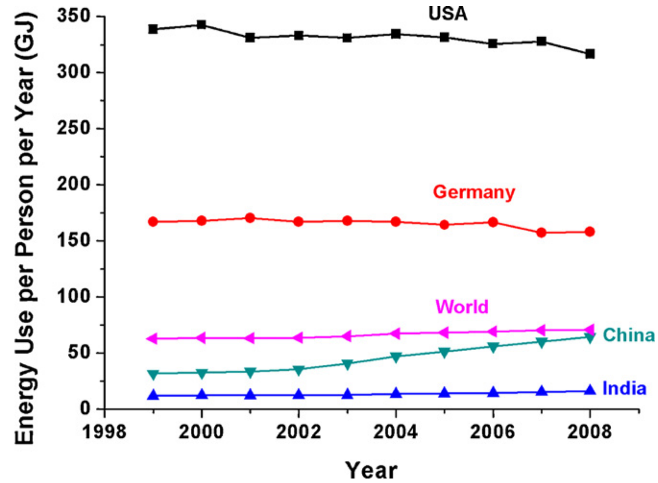


Fig. 2. Energy use per person – USA, Germany, China, India, and the World.

use of energy-efficient technology, average winter and summer temperatures, etc. Therefore, different countries have different consumption values of energy use per person.

Fig. 2 shows energy use per person per year during a ten year period (from 1999 to 2008) for The United States, Germany, China, India, and the World [11–17]. The United States consumes more energy per person than any other country in the world [18]. USA and Germany, however, show a slight decrease in the energy use per person near the end of these ten years. On the other hand, India and China, which are typical examples of rapidly growing economies from the developing world, show an increase in the energy use per person during this period. The World, as whole, also shows an increase over this period due to sharper increase in energy use by some rapidly growing economies like Brazil, Russia, India and China (also known as BRIC) in the developing world. For our calculations of the energy consumptions in the future, i.e., from year 2100 onward, we will assume a value of 250 GJ energy use per person in the world which is approximate average for energy use per person in the USA and Germany during this time period, i.e., from 1999 to 2008.

USA and Germany both fall in the world's richest countries' category. However, the energy use per person in the USA is almost double than in Germany. The general reasons for this are discussed above. Specifically in case of Germany, for example, there is more energy dependence on foreign resources, leading to a culture of economic energy-use policy, compact and better insulated housing-units compared to USA, and (to some extent) due to less-severe average winter-and-summer temperatures compared to USA.

Table 1 shows world's primary energy consumption from year 2004 to 2009 [12–17]. It shows an average annual increase of 1.6% in these years. As will be discussed later that this average annual increase of ∼1.6% of the world from 2004 to 2009 is almost equal to the average annual increase of 1.75% from year 2009 to 2100 (calculated next).

Table 1
World primary energy consumption (EJ) in the years from 2004 to 2009 [12–17].

Year	Oil	Natural gas	Coal	Nuclear	Hydro	Total	% increase
2004	159.0	101.5	117.2	26.2	26.9	430.9	
2005	161.7	105.2	123.8	26.3	27.9	444.8	3.1
2006	163.7	107.1	127.3	26.6	29.2	454.0	2.0
2007	164.9	111.0	133.7	26.1	29.1	464.9	2.4
2008	165.8	113.8	137.6	26.0	30.6	473.7	1.9
2009	162.5	111.1	137.3	25.6	31.0	467.4	−1.4

Average increase from 2004 to 2009 = 1.6%.

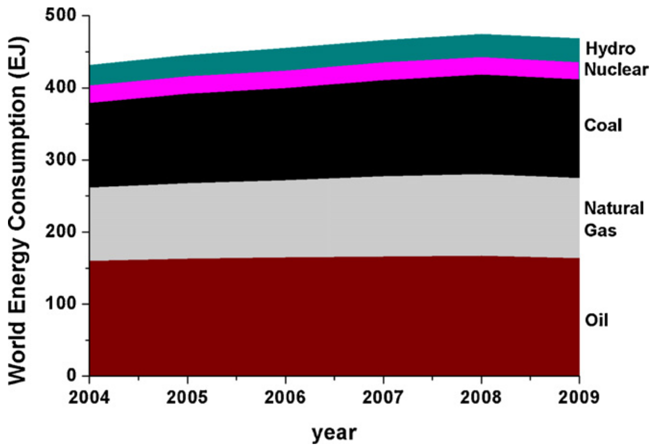


Fig. 3. World primary energy consumption during the past five years from 2004 to 2009.

Fig. 3 is plotted using the data in Table 1 and shows the world's primary energy consumption in the past five years, i.e., 2004–2009. The major share in the energy market, as shown in the figure, comes from oil, followed by coal and natural gas. Thus fossils at this stage contribute more than 80% in the total energy requirements of the world.

2. Major energy sources

2.1. Sun-dependent energy sources (SDES)

Major sun-dependent energy sources (SDES) are solar, hydro, biomass, wind, tidal, wave, ocean thermal energy conversion, etc.

2.2. Sun-independent energy sources (SIES)

Major sun-independent energy sources are geothermal, nuclear fission and nuclear fusion.

3. Current/future energy use options

There are few misconceptions about energy resources even among the scientific community. For example, that the sun-dependent energy sources (SDES), and even the sun-independent energy resources are inexhaustible which, as we have seen, is not true. The period for current/future energy resources and their utilization can be divided into: fossil era, transition era and post-fossil era as shown in Fig. 4. It shows world's primary energy demand/consumption in the future and is based on high, medium, and low population projections [9] and assuming an average consumption of 250 GJ per person after year 2100. In the post-fossil era, there are three possible scenarios for the world's primary energy consumption values depending upon the three population projection scenarios of the world [9]. However, for further discussion only the medium projection scenario is used which depends on the assumption that world population will reach close to its maximum value between 9 and 10 billions and will largely remain constant afterward. A similar scenario was also predicted in another UN report [10]; therefore, all further calculations for future are based on this medium level projection of the world population.

3.1. Fossil era

Fossil era is very short in time-length when compared to post-fossil era which is extending up to million and billion of years. Until recently, i.e., 2010, fossil fuels dominate in the fuel market and we are going through the peak-time of fossil fuels. That is why the period until 2010 in this article has been termed as fossil era. After that, i.e., 2011–2100, the transition era starts because in this period the dominant status of fossil fuels will change and they will be gradually replaced with the alternate fuels. The fate of fossil fuels regarding their exit time will also be decided in this period.

3.2. Transition era

This era lies between the fossil and the post-fossil eras. In this era, the fate of many traditional fuel sources, like fossils and nuclear (fission based), will be decided. Uranium based fuel are expected to last approximately 85–90 years based on current reserves and will eventually deplete within the current century [17,19,20] if

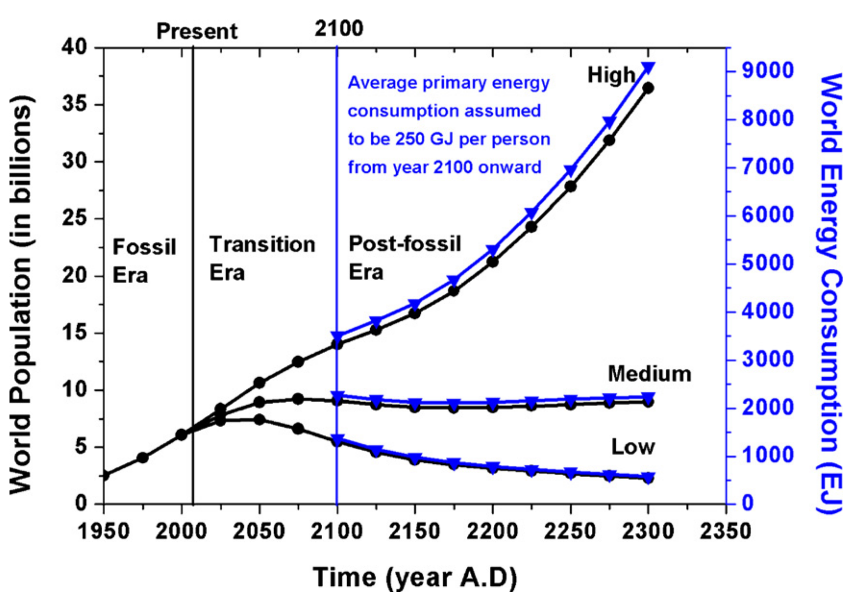


Fig. 4. World primary energy demand/consumption in the future, based on high, medium, and low population projections and assuming an average consumption of 250 GJ per person from year 2100.

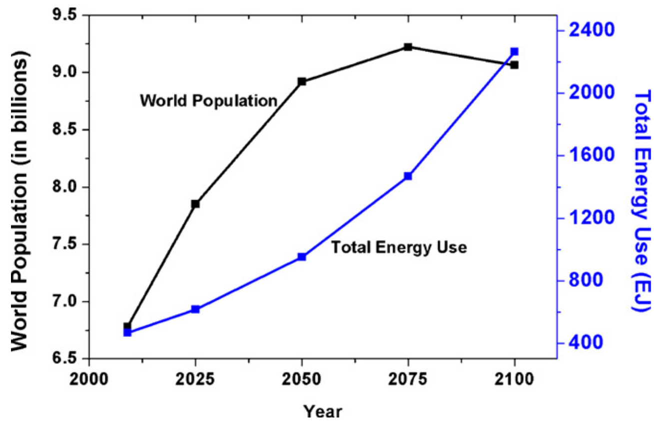


Fig. 5. World population and total energy use in the current century – transition period.

fast breeder reactors do not replace the existing nuclear power plants. Public acceptability, especially after some severe nuclear accidents in the recent past, is a big question even if the fission based fast-reactor technology is ready to replace the current technology. Therefore, fission based nuclear reactors are less likely to continue in the 22nd century. Similarly, the next few decades within the current century will also decide the feasibility and starting point (for commercial availability) of fusion energy. Although fusion energy (as will be discussed later) is almost certain to play a major role in the future energy supplies, the only uncertainty is the starting point for its commercial availability and the future energy-use policy.

There are a number of scenarios and projections for fossils being wiped-out from the planet making it hard to speculate a date or exact year for their phase-out. However, in the long time-scale of energy-use, we can safely deduce the expected century for different fossil fuels' exit, for example, 22nd century for oil and gas, and 23rd or 24th century for coal. Fossil fuels will have their peak in the current (21st) century but within the same century their share will reduce from dominant to meager.

Fig. 5 shows variation of world population (assuming a medium level increase according to UN estimates [9]) and total energy-use by the world. The total energy use during this transition period was calculated by assuming an average annual increase of 1.75% in energy consumption by the world. This annual increase was calculated by using the total primary energy consumption value in 2009 [12] and 2100. The annual energy consumption in 2100 was calculated from our energy-use per person value of 250 GJ (average of current energy use per person by two advanced countries. i.e., USA and Germany) and the world population value of 9.064 billion according to medium-level-increase projection of UN estimates [9]. This average annual increase of 1.75% (from year 2009 to 2100) in world's primary energy consumption is almost equal to the average increase of ~1.6% in the past five years, i.e., from 2004 to 2009 [12–17].

3.3. *Post-fossil era*

Post fossil era can be further divided into the sun-dependent energy sources era and sun-independent energy sources era.

3.3.1. *Sun-dependent energy sources era*

The sun-dependent energy sources era will last another 5–10 billion years from now. Table 2 summarizes the theoretical and technical potential and availability time for sun-dependent energy sources. It is to be noted that only theoretical and technical potentials are considered in Tables 2 and 3 and not the economic potential assuming that after technological advancement from year 2100, the economic potential might not be a constraint in the extraction of energy from different sources.

Among these sun-dependent energy sources, the biggest source is directly the sun itself, i.e., the solar energy. The technical potential for solar energy is greater than 1575 EJ per year [19] and it alone can meet around 70% of the world's total energy requirements of ~2300 EJ/year after year 2100. The availability time for direct solar energy is as long as the life of the sun itself, i.e., 8–10 billion years. The second biggest source is wind energy and has a technical potential of around 640 EJ/year [19]. The availability time for this source is around 5–7 billion years. The technical potential of biomass is around 276 EJ/year and its availability time is around 5 billion years. Technical potential of hydro power is around 50 EJ/year with availability time of around 5 billion years. Similarly, the technical potential of the ocean energy is around 74 EJ/years [19] (assuming a conservative 1% of theoretical potential of 7400 EJ/year) and its availability time is also around 5 billion years.

3.3.2. *Sun-independent energy sources era*

The sun-independent energy sources include geothermal and nuclear (both fission and fusion). Among these sources, uranium will deplete first based on current reserve estimates [17,19,20]. Uranium reserves will exhaust approximately in the same time-period in which fossil fuels, especially oil and gas, will be depleted.

Uranium based fuels, as discussed previously, might be wiped out even earlier in the wake of some serious accidents, e.g., at reactor 4 of Chernobyl nuclear power plant [21] and reactors 1–4 of Fukushima-Daiichi nuclear power plant in Japan [22]. However, unit 4 at Fukushima did not involve any reactor core or spent fuel storage accident but only the reactor building was damaged [22]. Therefore, a major disadvantage of the nuclear accident is that the other reactor units, though completely intact, like units 5 and 6 at Fukushima, become inoperable, in addition to making a vast surrounding area uninhabitable around the plant [23].

These accidents, therefore, could consequently speed-up early exit of nuclear (fission) power plants if the public unacceptability increases especially after Japan which is a developed country and uses relatively modern and safer nuclear power plant technology compared to that used at Chernobyl [21].

Even if uranium based fuels are continued to be used, they are not in sufficient quantities to last more than 100 years [17,19,20]. Therefore, the most important sun-independent energy source is fusion. Table 3 summarizes the theoretical and technical potential, and availability time of two important sun-independent energy sources, i.e., geothermal and fusion. Again, the economic potential is not considered as a limiting factor at this stage assuming that after the technological advancement from year 2100, the economic potential may no longer be a constraint in extraction of energy from geothermal and fusion sources.

USA is estimated to have a geothermal energy of 14×10^6 EJ from a depth of 3–10 km [24]. Upper limit is 40% recovery but if a midrange of 20% recovery is considered, the total energy amounts to 2.8×10^6 EJ. The results for the world are extrapolated from the USA estimates. A rough estimate for the world (as USA has ~5–10% of the world's geothermal energy) would give a value of ~2.8×10^7 EJ recoverable geothermal energy and a total potential of 1.4×10^8 EJ for a depth of 3–10 km.

The availability time for geothermal energy is approximately 12,000 years assuming 100% share of the total energy requirement (2300 EJ/year) is met from geothermal energy. In case of fusion, however, the availability period is extended from million up to billion years depending upon the assumptions involved. The total theoretical potential for fusion energy is 1.564×10^{13} EJ. If total energy demand of 2300 EJ/year is met from fusion, the availability time for fusion energy is approximately 68 million years, assuming

Table 2
SDES – theoretical and technical potential, and availability [19].

Energy resource	Theoretical potential (EJ/year)	Technical potential (EJ/year)	Availability (billion years)
Hydro	146	50	5
Solar	3.9×10^6	1575	8–10
Wind	6000	640	5–7
Biomass	2900	276	5
Ocean	7400	74 (conservative 1% of theoretical potential)	5
Total	3.92×10^6	2615	5–10

Table 3
SIES – theoretical and technical potential, and availability [24,25].

Energy resource	Theoretical potential (EJ)	Technical potential (EJ)	Availability (years)
Geothermal	1.4×10^8 (from a depth of up to 3–10 km)	2.8×10^7	~12,000 years (with 100% share of total requirement of 2300 EJ/year)
Fusion	1.564×10^{13}	1.564×10^{11} (conservative 1% of theoretical potential) 1.564×10^{12} (10% of theoretical potential) 7.82×10^{12} (50% of theoretical potential)	~68 million years (with 100% share of total requirement of 2300 EJ/year) ~680 million years (with 100% share of total requirement of 2300 EJ/year) ~3.4 billion years (with 100% share of total requirement of 2300 EJ/year)

a technical potential of 1.0% of the theoretical potential. The availability time is increased to ~680 million years and ~3.4 billion years if we consider a technical potential of 10% and 50% of the theoretical potential, respectively. Based on these assumptions, it is recommended that an ultimate energy-use policy should be evolved and adopted on global level rather on local or country level, especially after the year 2100.

Fig. 6 shows a possible and recommended energy use scenario after year 2100. In this scenario the stress is laid on the sun-dependent energy sources as they are constantly available and eventually 'lost' if not utilized unlike the sun-independent energy sources which offer long-term energy storage solution. Fusion materials are the best example for that as they are stable nuclei and hence offer the best long-term solution of energy storage. Therefore, their use is only recommended up to 1% in this SDES dominant scenario in order to gain the necessary experience in the use of fusion technology.

The SIES' best possible use starts after the share of sun-dependent sources starts to decline largely because of the sun itself, when it eventually starts running out of its fusion fuels.

The second most important medium to long term energy storage solution is the geothermal source, but unlike fusion it only offers an interim storage solution. Therefore, it can be used during the SDES era, i.e., in periods where we need extra energy and the demand for which cannot be met from the sun-dependent energy sources. As a result, their use is not predicted precisely in this scenario and can be used intermittently in periods where the need for their use arises.

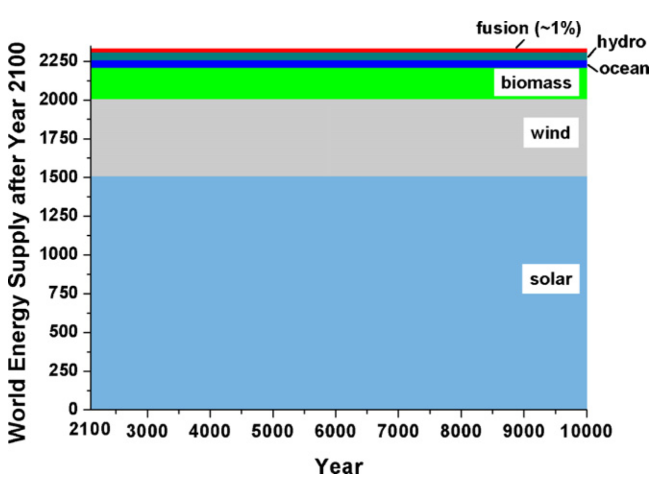


Fig. 6. Long-term energy supply after year 2100 – recommended share.

4. Conclusion

As discussed earlier, there are few misconceptions about energy resources that the sun-dependent energy sources (SDES) and the sun-independent energy resources are inexhaustible. Broadly, the period for future energy resources and their utilization can be divided into: fossil, transition, and post-fossil eras. Fossil and transition eras are very short in time-scale compared to post-fossil era which is extending up to billion of years. Post fossil era can be further divided into sun-dependent energy sources (dominant) era, a second transition period (from SDES to SIES), and lastly sun-independent energy sources (dominant) era. The sun-dependent energy sources era will last for 5–10 billion years while sun-independent energy sources era will last for up to few billion years depending upon the policy. For example, if we consume all of the fusion materials in the same period where we have abundant supply of sun-dependent sources then we may not have a sun-independent energy sources era. Therefore, the future is in our hands *now* and we can decide how long and how efficiently we will use different energy sources. The same has been discussed and highlighted in this paper.

It is therefore recommended that in this current transition period, more focus is given to the development of new technologies for efficient use of SDES before fossils and uranium fuels are phased-out. The research on the most important SIES, i.e., fusion should be limited only to make it feasible for commercial availability and to gain necessary technical experience. But its share should not be increased by more than 1% of the total energy requirement of the world as they offer the best long-term energy storage solution and should not be used when SDES are available in abundance.

References

[1] Siraj MS.Proceedings of AIChE annual meeting. 2009, 350d.
[2] Capehart BL. Encyclopedia of energy engineering and technology. CRC Press; 2007.
[3] Serway RA, Moses CJ, Moyer CA. Modern physics. 3rd ed. Thomson Learning Inc.; 2005.
[4] Zumerchik J. Macmillian encyclopedia of energy, vol. 1. USA: Macmillian Reference; 2001.

[5] Meyers RA. Encyclopedia of physical science and technology—energy. 3rd ed. Elsevier Science Ltd.; 2001.
[6] Okun LB. Energy and mass in relativity theory. World Scientific Publishing Co. Pte. Ltd.; 2009.
[7] Perkins DH. Introduction to high energy physics. 3rd ed. Cambridge University Press; 2000.
[8] Halliday D, Resnick R, Walker J. Fundamentals of physics. 8th ed. John Wiley & Sons, Inc.; 2007.
[9] World population to 2300. United Nations, New York: Population Division; 2004. ST/ESA/SER.A/236.
[10] The World at Six Billion, ESA/P/WP.154, UN Population Division, October 1999.
[11] US Census Bureau, International Data Base (IDB) <http://www.census.gov/ipc/www/idb/country.php>; 2011. Online (03.01.2011).
[12] BP statistical review of world energy, June 2010. British Petroleum; 2010.
[13] BP statistical review of world energy, June 2009. British Petroleum; 2009.
[14] BP statistical review of world energy, June 2008. British Petroleum; 2008.
[15] BP statistical review of world energy, June 2007. British Petroleum; 2007.
[16] Quantifying energy, BP statistical review of world energy, June 2006. British Petroleum; 2006.
[17] Survey of Energy Resources, World Energy Council, 2010.
[18] Annual Energy Review 2009, DOE/EIA-0384(2009) <http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf>; August 2010. Online (28.04.2011).
[19] World Energy Assessment, Energy and the Challenge of Sustainability, United Nations Development Programme <http://www.undp.org/energy/activities/wea/drafts-frame.html>; 2000. Online (28.04.2011).
[20] <http://www.iaea.org/newscenter/news/2006/uranium_resources.html>; 2011. Online (28.04.2011).
[21] INSAG-7, The Chernobyl accident: updating of INSAG-1, IAEA Safety Series No. 75-INSAG-7, International Atomic Energy Agency, Vienna, 1992.
[22] <http://www.slideshare.net/iaea/table-summary-of-reactor-unit-status-at-27april0700-utc>; 2011. Online (28.04.2011).
[23] <http://www.iaea.org/newscenter/news/tsunamiupdate01.html>; 2011. Online (28.04.2011).
[24] MIT Report, The Future of Geothermal Energy, <http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf>; 2006. Online (28.04.2011).
[25] Hamacher T, Bradshaw AM. Fusion as a future power source: recent achievements and prospects. In: 18th world energy congress. 2001.